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UNMANNED COMBAT AIR VEHICLE (UCAV) AUTOMATED REFUELING SIMULATION DEVELOPMENT

Delivery Order 0009: Volume 2 - KC-135

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An experimental investigation was conducted in the Langley Full Scale Tunnel (LFST) to collect the data necessary to model the effects of the wake of a KC-135 tanker on the aerodynamics of a similar scale UCAV-like aircraft (ICE101 configuration) in a refueling scenario. The primary efforts of this task were to measure the aerodynamic forces and moments on the ICE101 model in the presence of the KC-135 wake and then create aerodynamic increments for use in taking and formation simulation. A secondary undertaking was to conduct a flow survey behind the KC-135 model to quantify its wake characteristics.

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TABLE OF CONTENTS

Section .... Page

TABLE OF CONTENTS .... **III**

LIST OF TABLES .... **IV**

LIST OF FIGURES .... **V**

1.0 INTRODUCTION **1**

2.0 NOMENCLATURE **2**

3.0 EXPERIMENTAL INVESTIGATION **3**

3.1 TEST FACILITY 4
3.2 DESCRIPTION OF MODELS 6
3.3 TEST CONDITIONS 9
3.4 AERODYNAMIC FORCE AND MOMENT MEASUREMENT 12
3.5 WAKE PRESSURE MEASUREMENT 14

4.0 DATA PRESENTATION **17**

REFERENCES **34**

LIST OF TABLES

Table 1. Dimensional reference values for the KC-135 and ICE101 models. 8
Table 2 Test Program For UCAV/KC-135 Refueling Flight Formations. 10
Table 3: Calibrated values for probe 1A. 16

LIST OF FIGURES

Figure 1. Schematic of the Langley Full-Scale Wind Tunnel. 4
Figure 2. UCAV/KC-135 Aerial Refueling Test Setup... 5
Figure 3. Three-view sketch of the Boeing KC-135. 7
Figure 4. Three-view drawing of the ICE 101 configuration. 7
Figure 5 Test points for the UCAV/KC-135 refueling data. 11
Figure 6. Five-hole probe #1A. 14
Figure 7. Survey probe mounted on test section floor sting.. 16
Figure 8. Axial force increment produced by KC-135 on ICE 101 at AOA=4°. 19
Figure 9. Axial force increment produced by KC-135 on ICE 101 at AOA=7°. 20
Figure 10. Normal force increment produced by KC-135 on ICE 101 at AOA=4°........ 21
Figure 11. Normal force increment produced by KC-135 on ICE 101 at AOA=7°........ 22
Figure 12 Pitching moment increment produced by KC-135 on ICE 101 at AOA=4°. . 23
Figure 13. Pitching moment increment produced by KC-135 on ICE 101 at AOA=7°. 24
Figure 14. Side force increment produced by KC-135 on ICE 101 at AOA=4°............ 25
Figure 15. Side force increment produced by KC-135 on ICE 101 at AOA=7°............ 26
Figure 16. Rolling moment increment produced by KC-135 on ICE 101 at AOA=4°. .. 27
Figure 17. Rolling moment increment produced by KC-135 on ICE 101 at AOA=7°. .. 28
Figure 18. Yawing moment increment produced by KC-135 on ICE 101 at AOA=4°. . 29
Figure 19. Yawing moment increment produced by KC-135 on ICE 101 at AOA=7°. . 30
Figure 21. Angle of attack flowfield variations produced by KC-135 at AOA=2°.......... 31
Figure 23. Angle of sideslip flowfield variations produced by KC-135 at AOA=2°. 32
Figure 22. Dynamic pressure flowfield variations produced by KC-135 at AOA=2°..... 33

1.0 INTRODUCTION

In order to develop robust automated refueling controls and strategies, a model of the aerodynamic characteristics in the wake of a tanker aircraft is needed. An experimental investigation was conducted in the Langley Full Scale Tunnel (LFST) to collect the data necessary to model the effects of the wake of a KC-135 tanker on the aerodynamics of a similar scale UCAV-like aircraft (ICE101 configuration) in a refueling scenario. The primary efforts of this task were to measure the aerodynamic forces and moments on the ICE101 model in the presence of the KC-135 wake and then create aerodynamic increments for use in tanking and formation simulation. A secondary undertaking was to conduct a flow survey behind the KC-135 model to quantify its wake characteristics.

Four electric ducted fans powered the KC-135 model. Fan thrust was scaled based on in-flight mass flow ratios of the full-scale aircraft. The ICE101 model was located at a variety of positions that included typical refueling situations as well as areas outside of the tanking envelope. Aerodynamic force and moment data were measured for the ICE101 model at each test location. The incremental coefficients are presented in Figures 8 through 19. These aerodynamic data were then implemented into an existing simulation of the ICE configuration to represent flight in the tanker wake.

To aid in understanding the effects of the taker flow field on the ICE101 aerodynamic data, a wake survey was conducted at the two closest locations to the KC-135 that were used for the ICE101 force and moment measurements. The results included local flow angle of attack and sideslip as well as dynamic pressure distribution and are presented in Figures 20 through 22.

2.0 NOMENCLATURE

The units for physical quantities used herein are presented in U.S. Customary Units. All aerodynamic data are referenced to the body system of axes.

b	wing span, ft
$b/2$	half the wing span (reference for data location), ft
$\bar{c}$	Mean aerodynamic chord, ft
C_A	axial-force coefficient, Axial force/$\bar{q}$S
C_L	lift-force coefficient, Lift force/$\bar{q}$S
C_N	normal-force coefficient, Normal force/$\bar{q}$S
C_Y	side-force coefficient, Side force/$\bar{q}$S
C_l	rolling-moment coefficient, Rolling moment/$\bar{q}$Sb
C_m	pitching-moment coefficient, Pitching moment/$\bar{q}S\bar{c}$
C_n	yawing-moment coefficient, Yawing moment/$\bar{q}$Sb
C_p	pressure coefficient, $(p-p_\infty)/\bar{q}$
LFST	Langley Full Scale Tunnel
p	port pressure, lb/ft^2
p_∞	free-stream static pressure, lb/ft^2
$\bar{q}$	free-stream dynamic pressure, lb/ft^2
S	wing area, ft^2
V	free-stream velocity, ft/sec
α	angle of attack, positive nose up, deg
β	angle of sideslip, positive for pilot's right ear windward, deg
Vinf	Velocity of the wind tunnel freestream airflow, ft/sec
Vjet	Velocity of the ducted fan exhaust flow, ft/sec

3.0 EXPERIMENTAL INVESTIGATION

Bihrle Applied Research, Inc constructed a 1/13-scale model of the KC-135 for this test. The KC-135 model represented a typical in-flight refueling configuration including engine nacelles, refueling boom, and elevator. In the wind tunnel, to best measure air vehicle response in formation with a tanker, the aerodynamic flow field shed by the tanker must be a good representation of the flow field of the tanker during refueling operations. To accomplish this, electrically powered ducted fans were mounted in the KC-135 model engine nacelles to produce the appropriate propulsive effects, providing the much needed jet wash effect to the flow field. Fan thrust was scaled based on in-flight mass flow ratios and distributed appropriately across the KC-135 model's four engines for a typical target mission: mean refueling condition (Alt=28,500, KIAS=274, Vt=697, Wgt=200,000 lbs). The motors were calibrated so the rpm of the ducted fan motors could be set to obtain a velocity ratio, Vjet/Vinf=3.4. A survey of the tanker's flowfield without any trailing aircraft was also conducted, using a five-hole pitot tube.

The wind-tunnel test matrix included adequate data coverage to facilitate the investigation of refueling control strategies and approach trajectories. Spatial variation was in three axes extending to regions where the tanker wake had no effect on the aerodynamics of the ICE 101 configuration. Force and moment data were collected from the ICE model at various positions in the wake of the KC-135. These points represent data taken across the vertical and lateral plane at four longitudinal positions. To reduce the size of the test matrix, span wise symmetry behind the KC-135 was assumed.

The KC-135 model was mounted through a top-sting arrangement attached to the Langley Full Scale Tunnel Survey Carriage. The overhead survey carriage was capable of translating in three directions, parallel and perpendicular, both horizontally and vertically to the tunnel freestream. The ICE 101 model was mounted on a small support attached to the test section ground board downstream of the KC-135 tanker.

3.1 Test Facility

The test was conducted at the Langley Full-Scale Tunnel, operated by Old Dominion University. It is housed in a 434-ft by 222-ft by 90-ft high building on the Langley Air Force Base in Hampton, VA. A schematic of the closed circuit facility is shown in Figure 1.

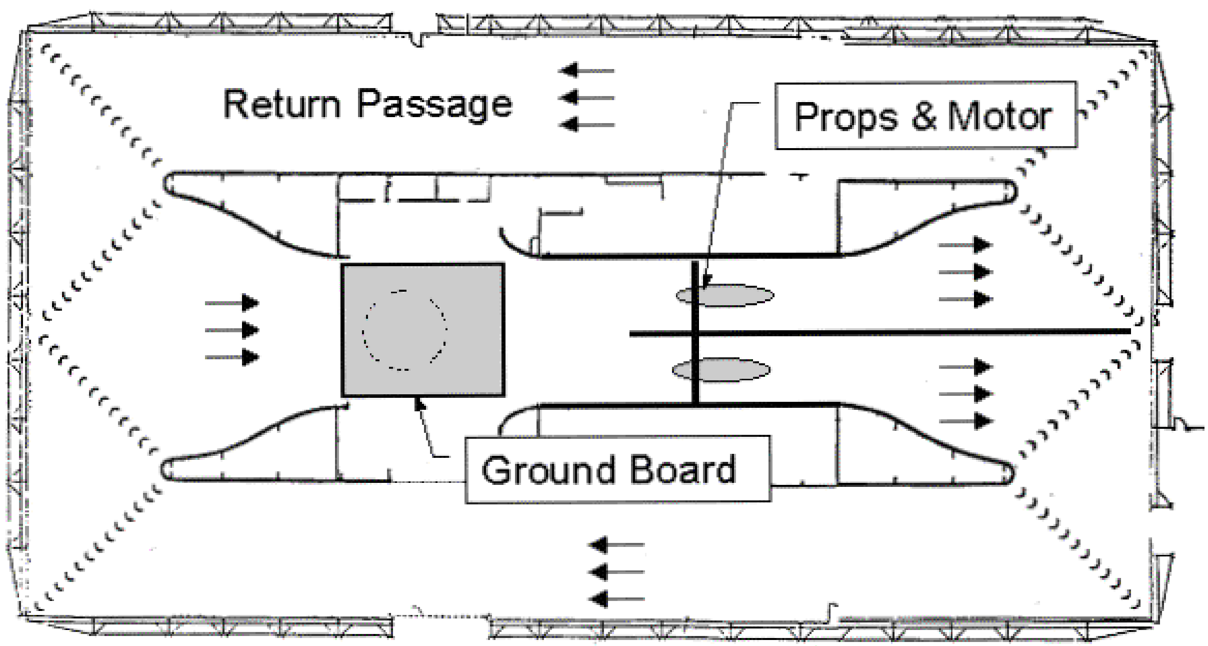


Figure 1. Schematic of the Langley Full-Scale Wind Tunnel.

The wind tunnel test section is 30-ft high by 60-ft wide by 56-ft long. It is a closed circuit, double return, open throat, continuous flow design that operates at atmospheric pressure. It is powered by two four-bladed, 35.5-ft diameter fans, each driven by a 4,000 HP electric motor, providing for a maximum speed of approximately 100 MPH.

The tunnel has an overhead survey carriage that is capable of translating in three directions, parallel and perpendicular, both horizontally and vertically to the tunnel free stream. Its movement range covers the entire planform of the test section from a height of 134 TO 247 inches above the ground board. The data acquisition computer automatically controls positioning of the carriage in the test section. Typically this carriage, as the name implies, is used to survey the tunnel by mounting an array of pitot tubes on the movable tip of the carriage. A pressure measurement system is then used to acquire dynamic pressure data to survey the desired area of the test section. For

these tests, however, the KC-135 was mounted to the overhead carriage. This allowed the model to be moved to any desired position.

For the wake survey behind the KC-135, a 5-hole pitot tube was mounted on a test stand located downstream approximately 2/3 of the test section length. The same test stand and position were used for the ICE101 measurements. For both the survey and the ICE101 tests the KC-135 was moved by the carriage to the desired test locations while the pitot tube and ICE101 model remained in a fixed position. Photographs of the KC-135 and ICE101 mounted in the tunnel are shown in Figure 2.

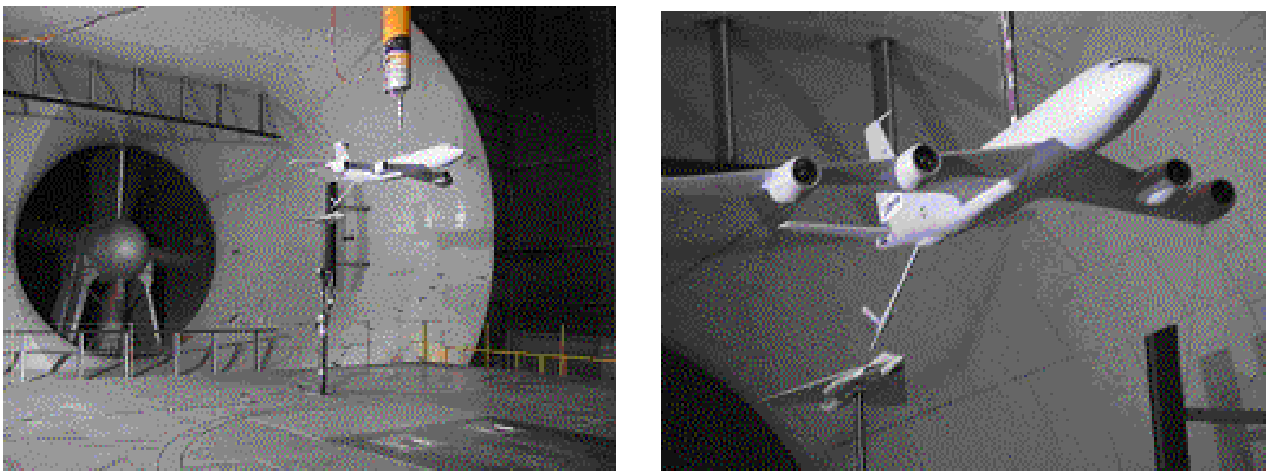


Figure 2. UCAV/KC-135 Aerial Refueling Test Setup

3.2 Description of Models

KC-135

A 1/13-scale model representing the KC-135 aircraft was constructed from fiberglass, balsa, foam, aluminum and plywood for these tests. The all-moving horizontal stabilator was constructed with the ability to lock it at any deflection angle within the specified maximum values 14° TE Up to 14° TE Down. The actual stabilator setting used for these tests was -8° (TEU). The moment center of the strain gauge balance was located at 32.0% of the MAC.

A multi-view sketch of the KC-135 aircraft is shown in Figure 3. Some full-scale dimensional characteristics of the aircraft are also listed in Table 1.

ICE101

A 1/13-scale model representing the ICE101 aircraft was constructed from fiberglass, balsa, foam, aluminum and plywood for these tests. The ICE type aircraft is a delta wing with no vertical or horizontal tails. It was originally designed and built to determine the effectiveness of innovative control surfaces. For these tests, all control deflections remained neutral. A three-view sketch of the ICE configuration is shown in Figure 4

The moment center of the strain gauge balance was located at 38.0% of the MAC. Some full-scale dimensional characteristics of the aircraft are also listed in Table 1.

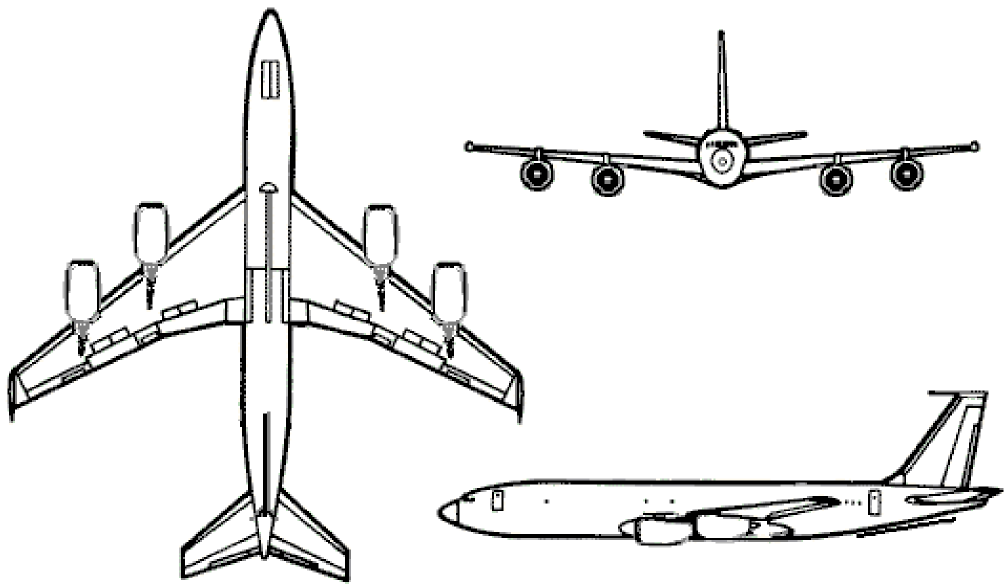


Figure 3. Three-view sketch of the Boeing KC-135.

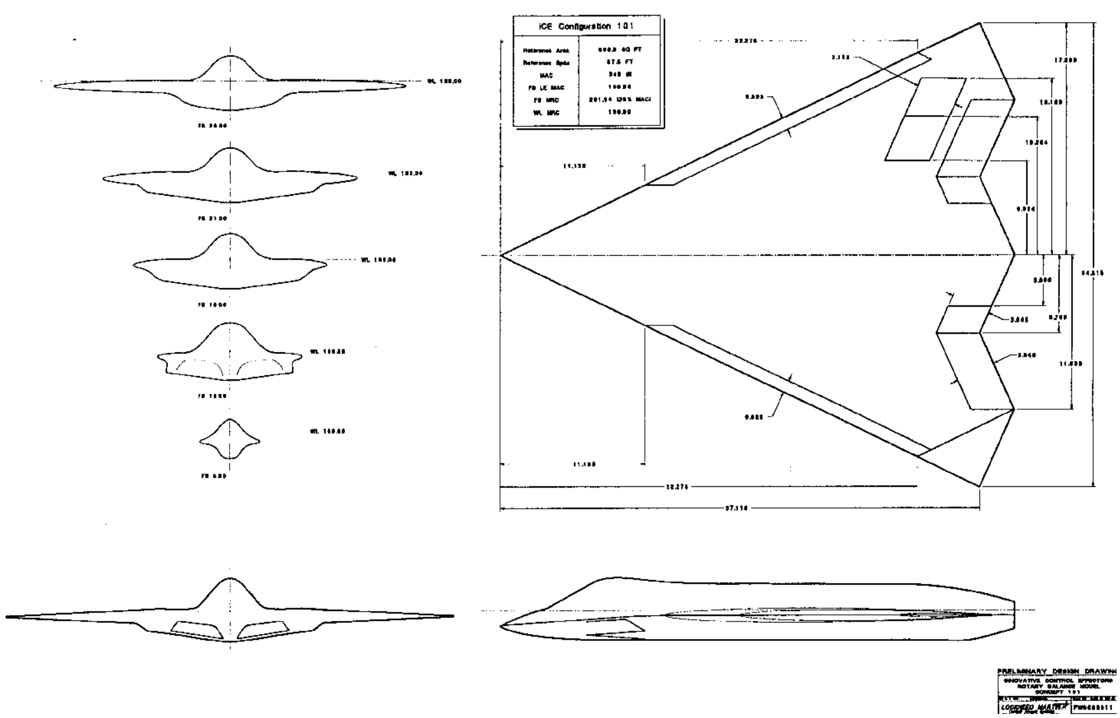


Figure 4. Three-view drawing of the ICE 101 configuration.

Table 1. Dimensional reference values for the KC-135 and ICE101 models.

	ICE101 Reference Dimensions		KC-135 Reference Dimensions	
	Model Scale (1/13)	Full Scale	Model Scale (1/13)	Full Scale
Length (ft)	3.30	42.90	10.48	136.25
Chord (ft)	2.21	28.74	1.55	20.16
Span (ft)	2.89	37.60	10.06	130.83

3.3 Test Conditions

The ICE101 data and flow survey were measured with the same conditions set for the KC-135 model: fixed angle of attack of 2 degrees, stabilator deflection of –8 degrees, engine thrust setting ratio of 3.4 with increased thrust of +10% outboard and decreased thrust of –10% inboard, and tunnel dynamic pressure of 5.0 psf. The appropriate thrust setting was determined by first calibrating engine rpm to the measured thrust ratio. The pitot tube was placed in the engine wake during this procedure.

For the ICE101 tests, the model was mounted to the strain gauge balance on the fixed groundboard sting. The KC-135 was moved to the desired positions and aerodynamic force and moment data was measured on the ICE model. The test setup of the two aircraft is shown in Figure 2. Data were collected at set spanwise, vertical, and longitudinal positions relative to the refueling formation. The locations are shown in Figure 5 and listed in a run program in Table 2. All distance are expressed in terms of the half span length (b/2) of the KC-135 model.

For the wake survey, a stationary 5-hole pitot tube replaced the ICE101 model and was used to measure the wake flow field behind the KC-135 tanker. The probe is shown mounted on the groundboard sting in figure 6. For the survey testing, the KC-135 was moved to the same locations as the previous ICE tests.

Tests were conducted at a dynamic pressure of 5 lb/ft^2, which corresponds to an air stream velocity of approximately 65 ft/sec. The Reynolds number based on model wing mean aerodynamic chord is 643,000 for the KC-135 and 917,000 for the ICE101.

Table 2 Test Program For UCAV/KC-135 Refueling Flight Formations.

KC-135 - ICE101 Refueling Test Parameters				
KC-135 Parameters	**Full Scale**	**1/13**		
Area (ft*ft)	2433.00	14.40		
Length (ft)	136.25	10.48		
cbar (ft)	20.16	1.55		
Span (ft)	130.83	10.06		**inches**
b/2 (ft)	65.42	**5.03**	**Scaling Parame**	**60.38**
ICE-101	**Full Scale**	**1/13**		
Length (ft)	42.90	3.30		
cbar (ft)	28.74	2.21		
Span (ft)	37.60	2.89		
b/2 (ft)	18.80	1.45		
Trail-Lead Ratios				
Ltrail/Llead	0.31	0.31		
cbartrail/cbarlead	1.43	1.43		
btrail/blead	0.29	0.29		
Spatial Increment	0.15	0.15		
Convention Relative to Tanker	**Positive**			
DX	Aft			
DY	Right Wing			
DZ	Up			
Block 0 Clean Air (Neutral Cont	**Min**	**Max**	**Inc**	**Num Points**
ICE AOA	0.00	12.00	2.00	7.00
	Min	**Max**	**Inc**	**Num Points**
ICE AOA	4.00	7.00	3.00	2.00
Block 1 (Boom extended)	**Min**	**Max**	**Inc**	**Num Points**
DX	1.25			1.00
DY	-2.20	0.00	0.20	12.00
	-0.60	-0.40	0.20	2.00
			Total	48.00
Block 2 (Boom Up)	**Min**	**Max**	**Inc**	**Num Points**
DX	1.70			1.00
DY	-2.55	0.00	0.15	18.00
DZ	-1.05	0.00	0.15	8.00
			Total	288.00
Block 3 (Boom Up)	**Min**	**Max**	**Inc**	**Num Points**
DX	3.00			1.00
DY	-3.00	0.00	0.15	21.00
DZ	-1.05	0.60	0.15	12.00
			Total	504.00
Block 4 (Boom Up)	**Min**	**Max**	**Inc**	**Num Points**
DX	6.00			1.00
DY	-3.00	0.00	0.15	21.00
DZ	-1.05	0.60	0.15	12.00
			Total	504.00

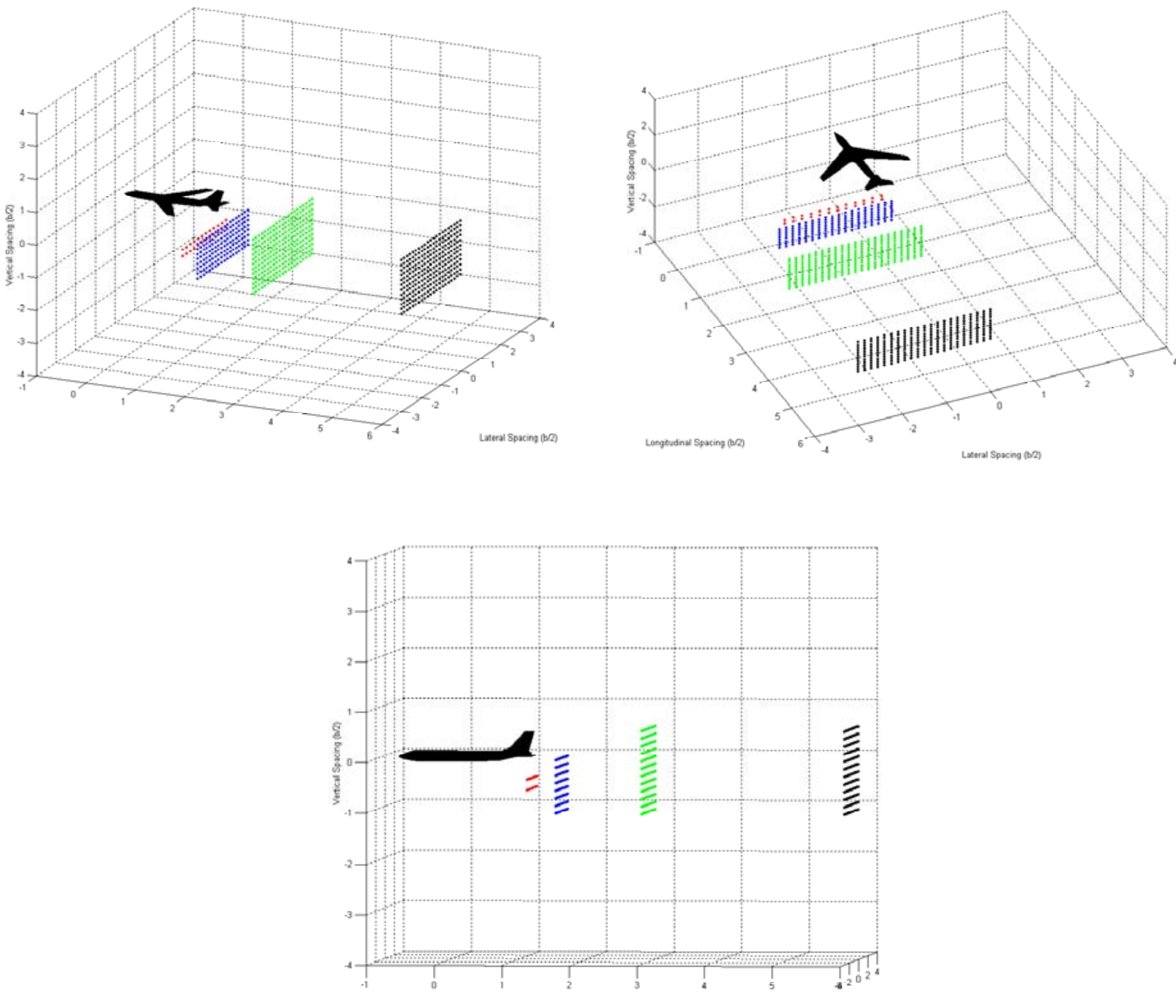


Figure 5 Test points for the UCAV/KC-135 refueling data.

3.4 Aerodynamic Force and Moment Measurement

To measure the aerodynamic force and moment data of the ICE101 model, a six-component strain gauge balance was used and mounted inside the model. The balance selected for the ICE model was the MAT-199A with normal force limits of 30 lbs. To be able to check the trim condition and attach it to the carriage sting, the 711 balance was used for the KC-135. It had a normal force limit of 500 lbs.

The strain gauge balances are constructed from a single piece of steel to measure six individual components. The only failures associated with these balances are overloading and yielding the material, loosening/damage of the strain gauges, or broken wires to or from the balance/gauges. All of these failures will show up in the data as some kind of erroneous electrical value that is converted into an incorrect force or moment.

To ensure that none of the above problems were present before the wind tunnel test the unloaded voltages on each component of the balance are measured. All of these types of balances have some zero load voltages on each component. These are removed from the measured values. These six measured voltages are stored and used by the data acquisition system to remove the electrical offsets.

At the beginning of testing after the model is installed, known loads are applied at the moment center of the balance as well as two to six inch offsets to check force and moment values. During the testing the balance outputs are checked by periodically taking air off data points and subtracting the tares to see that the aerodynamic coefficients remain zero with the tunnel airflow off.

The force and moment sensitivities and first and second order interaction coefficients for both balances have been supplied from the calibrations. The measured voltages are converted to forces and moments using the method described in reference 1.

These balances also use what is called “parallel wiring” and a power supply with voltage sensing capability. This provides a constant 5.00 volts of power to the balance bridges at all times and allows the direct use of the balance calibration values. A tunnel “span” does not have to be made with each data acquisition system to determine correction factors due to wiring, power supply differences, etc.

For static testing the tares (air-off values) are first measured for all angles of attack and sideslip that are desired. These values are stored for later use during air-on testing. For these tests only one angle of attack was tested. The tares provide the air off forces and moments of the model for all test attitudes. During static testing these values are subtracted from the air-on measurements leaving only the aerodynamic values. They are then converted to nondimensional coefficients based on the wind tunnel dynamic pressure and model reference geometry. These coefficient values along with test parameters and configuration information are stored for later plotting and analysis as well as use in the simulation database.

3.5 Wake Pressure Measurement

To measure the wake survey pressures, a 780B Pressure Measurement System from Pressure Systems, Inc. (PSI) was used; along with an electronic scanning pressure module. The plastic tubes from each port on the 5-hole probe were connected to one side of the differential pressure transducer. The transducer converted the pressures to voltages. The voltage level for each of the ports was sent to the Data Acquisition and Control Unit in the tunnel control room. The voltages for all ports were then passed to the tunnel computer for conversion to pressures, coefficients, and determination of the local flow angles of attack and sideslip and storage.

A photograph of the five-hole, hemispherical-head probe used in this program is shown in Figure 6. This type of probe is capable of sensing two components of flow angle in addition to total and static pressure. The linear range of the probe for flow angle measurements is generally ±20°. Probe 1A was borrowed from Old Dominion University (ODU) for use in these tests. The 5-hole probe calibration was conducted previously by ODU for use during their survey of the entire LFST test section.

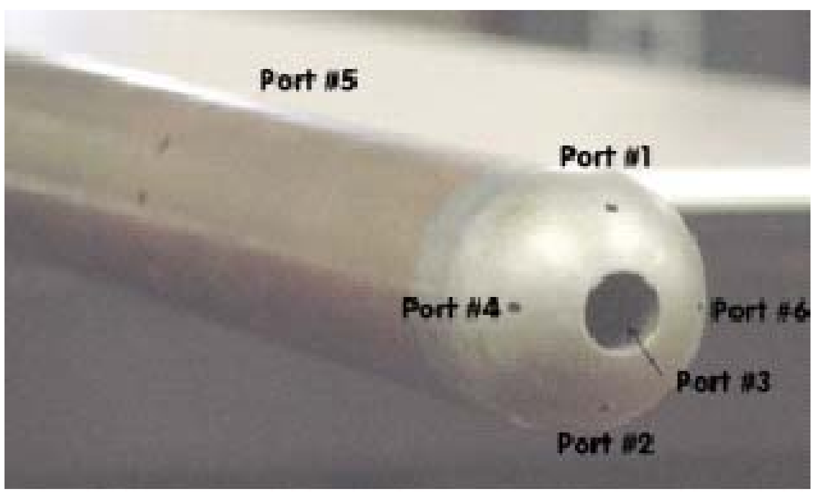


Figure 6. Five-hole probe #1A.

The pressure coefficients for these tests were measured as the difference in static pressure of opposing holes divided by the dynamic pressure. The dynamic pressure was measured using the pitot-static combination, subtracting the pressure

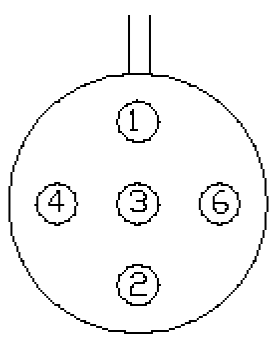
measured by the static ring port #5 to the total pressure measured by port #3. For the pitch data acquisition then, the pressure coefficient was defined as:

$$Cp_{(2-1)} = \frac{P_2 - P_1}{P_3 - P_5} \;;$$

while for yaw it was defined as: $$Cp_{(6-4)} = \frac{P_6 - P_4}{P_3 - P_5} \,.$$

It is important to note the angle convention that was used during the probe calibration measurement by ODU:

- When the probe measures a positive yaw angle, called β buy ODU, the stagnation point has moved to the west of the probe's axial centerline in the XY plane. The sign convention for the actual sideslip angle for this wake survey formation aircraft test was opposite to the yaw angle, described as β in the calibration. Because of this an extra negative sign has been added to the original calibration formula. This corrects the β sign convention to represent traditional sideslip angle, β.
- When the probe measures a positive pitch angle, α, the stagnation point has moved below the probe's axial centerline in the XZ plane.



Probe 1A port configuration (front view), Port #5 acts as the static port.

Table 3: Calibrated values for probe 1A.

	Probe 1A	
	Yaw (6-4)	Pitch (2-1)
A1	0.06790	0.06592
A2	0.06955	0.06985
A3	0.05152	0.04280
A4	0.06931	0.06984
ϕ	0.11644497	0.16542
Sensitivity (per degree)	0.0694303	0.069843
1/Sensitivity	14.40293	14.31785

From the ODU calibration results, the following formulas were supplied for calculating the local values of angle of attack and sideslip (β sign corrected):

$$\alpha = -0.165441969 + \left(C_{p_{(2-1)}}\right)(14.31785)$$
$$\beta = -\left[-0.116445 + \left(C_{p_{(3-4)}}\right)(14.40293)\right]$$

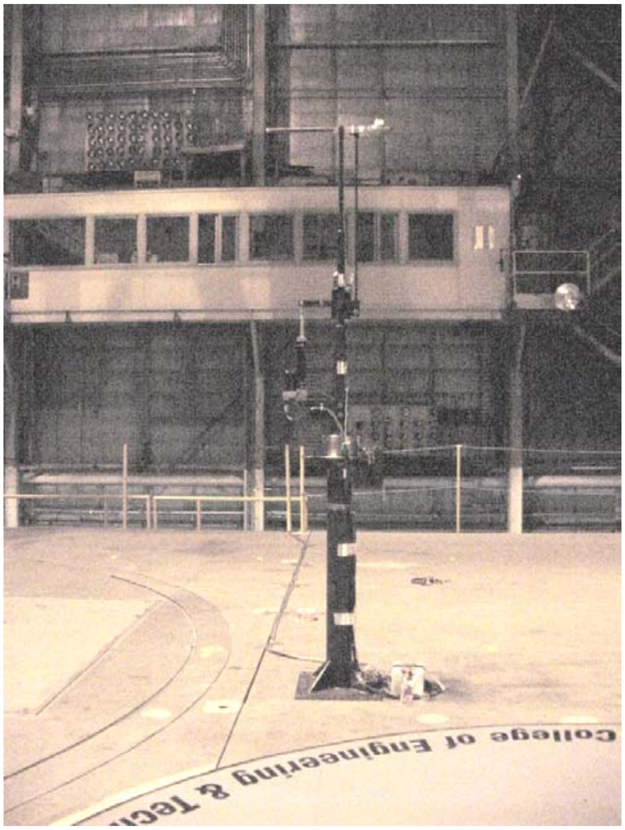


Figure 7. Survey probe mounted on test section floor sting.

4.0 DATA PRESENTATION

Various contour plots of the measured results from these force and moment and wake survey tests are shown in Figure 8 through Figure 22. For all of the plots, the x, y, and z locations of the data are expressed in distances equal to the number of half spans of the KC-135 model (b/2=5.03 ft). Figure 8 through Figure 19 present plots of the longitudinal and lateral/directional aerodynamic increments produced on the ICE 101 model at 4° and 7° angle of attack by the KC-135 model at the indicated test positions. Graphical views of the test locations for the ICE model (UCAV) behind the KC-135 are shown in Figure 5. Figures 20 through 22 show the survey results from part of the flow field behind the KC-135 powered model.

A silhouette of the KC-135 is superimposed on the contour plots to indicate its relative location. The results of aerodynamic force and moment measurements on the ICE101 model are shown in Figure 8 through Figure 19. The data presented are the incremental coefficients produced by the KC-135 flow field on the ICE101 model at four locations downstream from the KC-135. These distances are 1.2, 1.7, 3.0, and 6.0 b/2's behind the tanker. The data were only measured with the ICE model at points on the left side of the KC-135. The reference value for all forces and moments is 0. The colors on the contour plots show the force or moment changes experienced by the ICE model. Red indicates a positive value, blue a negative one, and green no change. Most noticeable are the rolling moment effects on the ICE 101 model when it is in the vicinity of the wing and stabilator tips of the KC-135. A positive value of rolling moment is produced when the ICE model is near the left wing tip due to the tip vortex flow. The stabilator tip has the opposite effect of the wing tip. It produces a negative rolling moment increment on the ICE model. The reason for the differences between wing and stabilator effects is probably due to the large trailing edge up setting of the stabilator (-8°) producing a positive pressure on its top surface. The effects of the KC-135 on the ICE model extend to the farthest distance tested (6.0b/2).

The flowfield data measured behind the KC-135 with the 5-hole pitot tube during these tests are presented in Figure 20 through Figure 22. Each figure has two plots representing incremental results in a plane at distances of 1.2b/2 and 1.7b/2 (Figure 5)

behind the KC-135. The results at the 1.2b/2 location are limited an area 0.5b/2 below the model. The reference values for the survey were 0° angle of attack and sideslip and 5.0 psf dynamic pressure. For all plots positive increments from the reference values are indicated by red contour lines while blue ones indicate negative values. In Figure 20, the angle of attack variations are shown. Positive angle of attack flow is seen outboard of the wing tip while negative values occur behind the engine nacelles. The sideslip angle variations are shown In Figure 21. Positive sideslip angle is produced inboard of the wing tip while negative values are indicated between the engine and fuselage. The dynamic pressure variations are shown In Figure 22. At these distances, a decrease is seen behind the inboard engine.

All of the force and moment and survey data measured in this test entry have been converted to ASCII format and provided on CD-ROM.

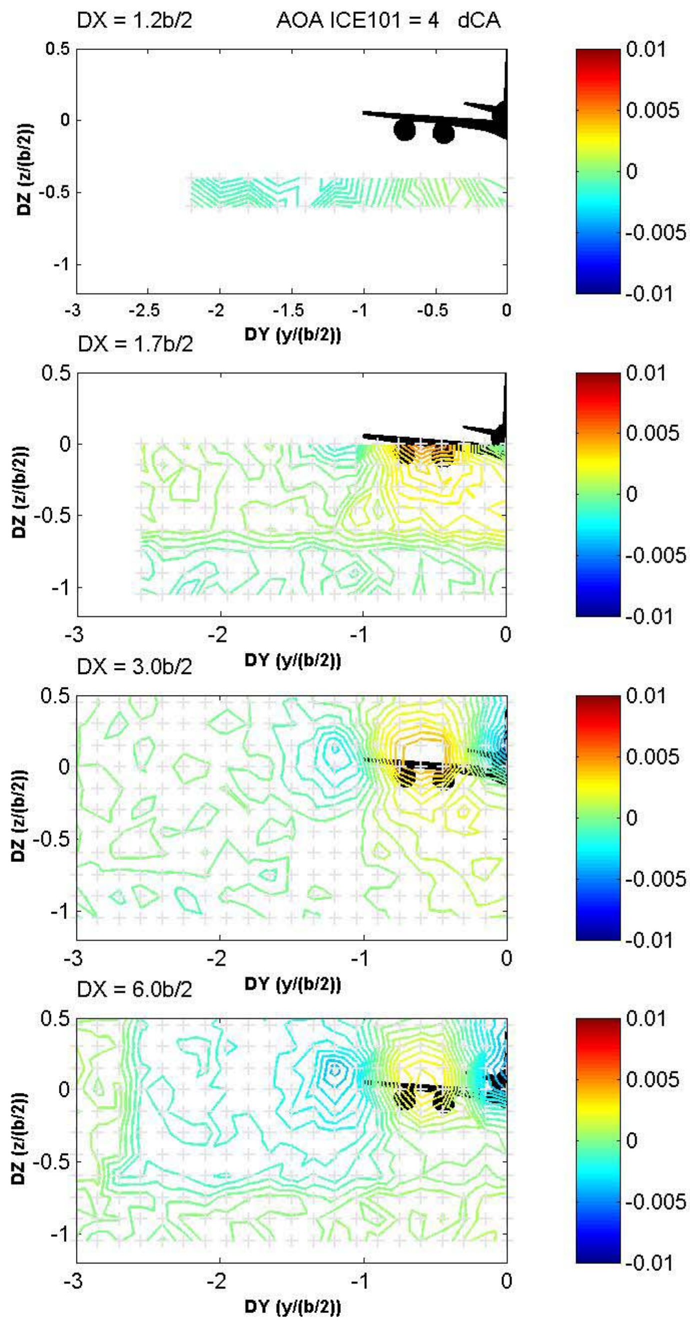


Figure 8. Axial force increment produced by KC-135 on ICE 101 at AOA=4°.

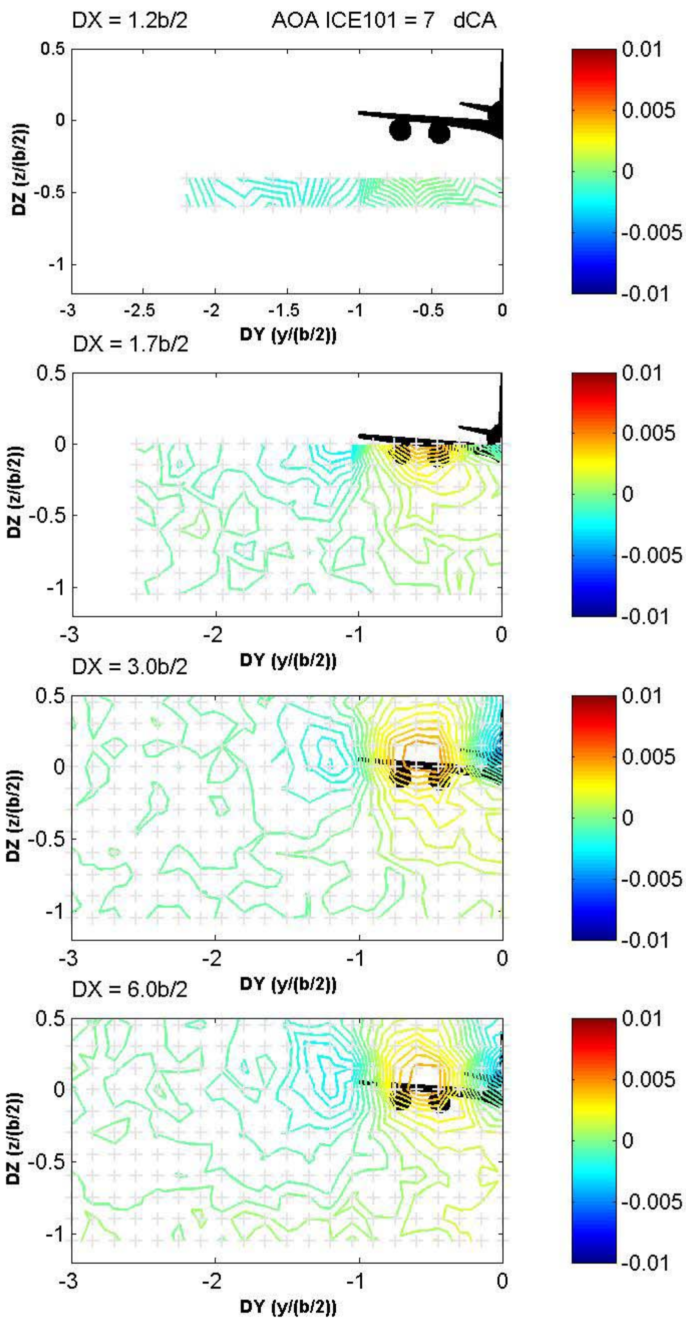


Figure 9. Axial force increment produced by KC-135 on ICE 101 at AOA=7°.

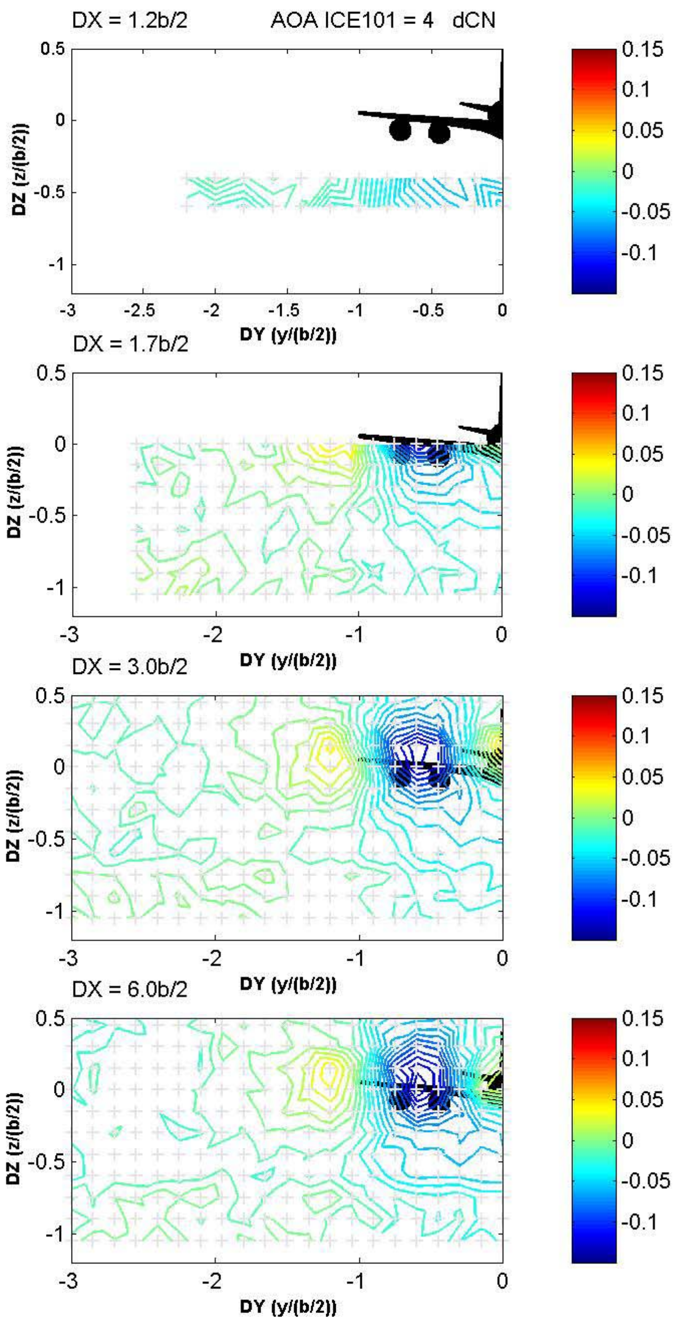


Figure 10. Normal force increment produced by KC-135 on ICE 101 at AOA=4°.

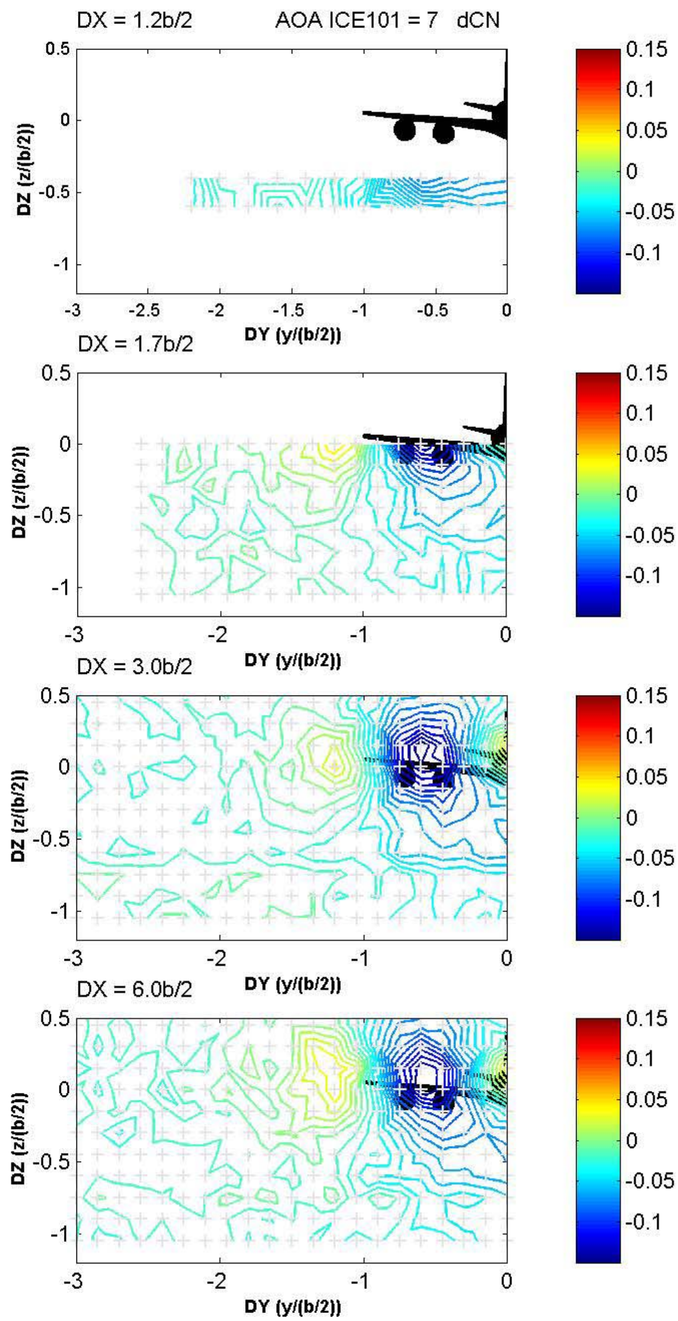


Figure 11. Normal force increment produced by KC-135 on ICE 101 at AOA=7°.

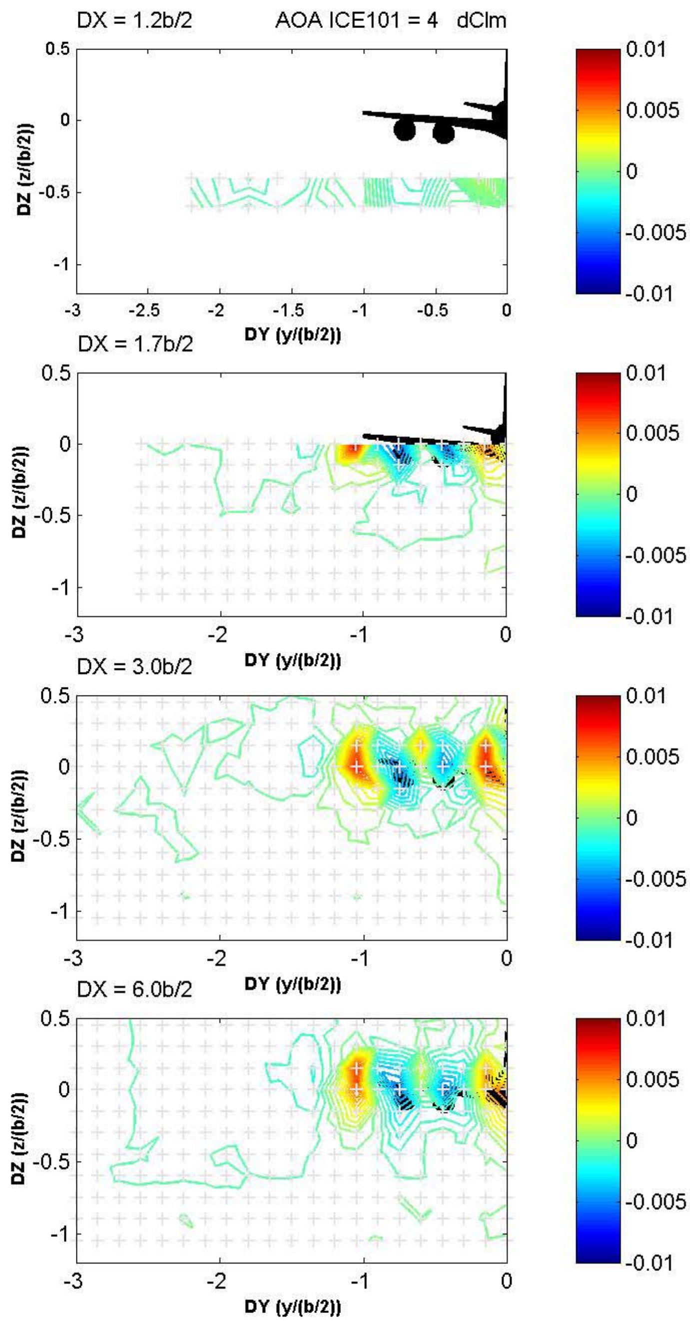


Figure 12 Pitching moment increment produced by KC-135 on ICE 101 at AOA=4°.

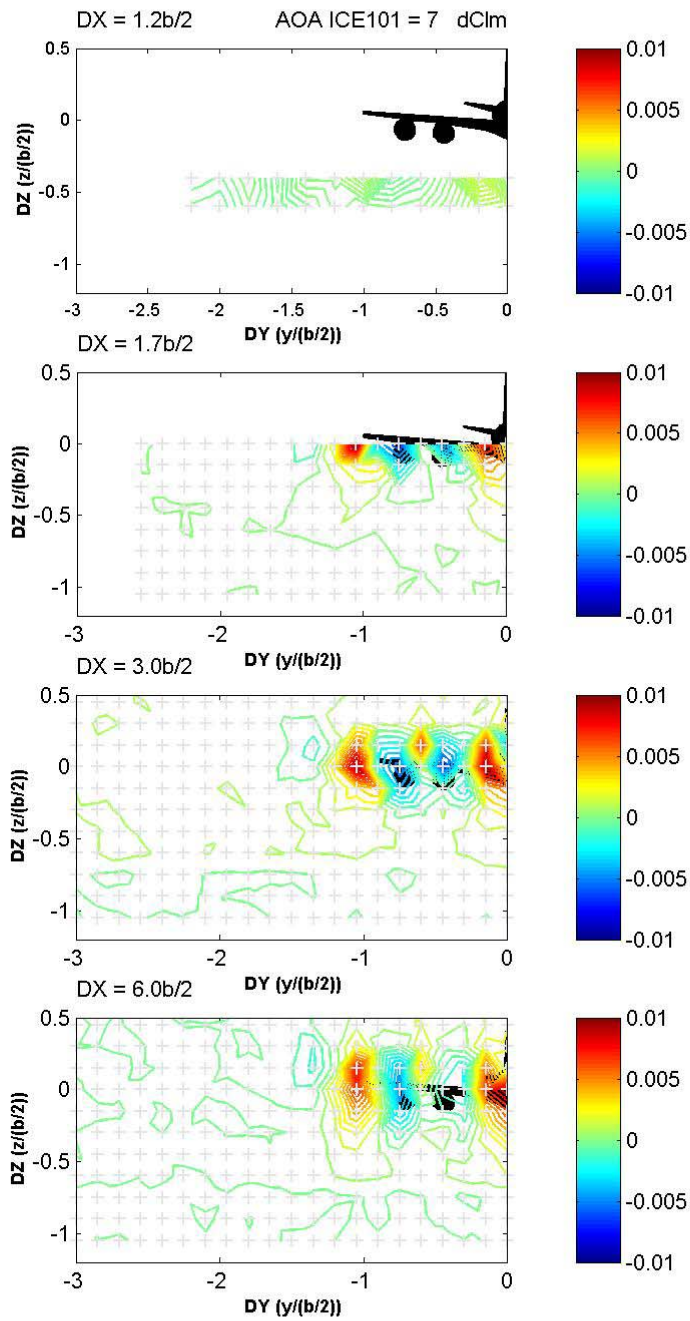


Figure 13. Pitching moment increment produced by KC-135 on ICE 101 at AOA=7°.

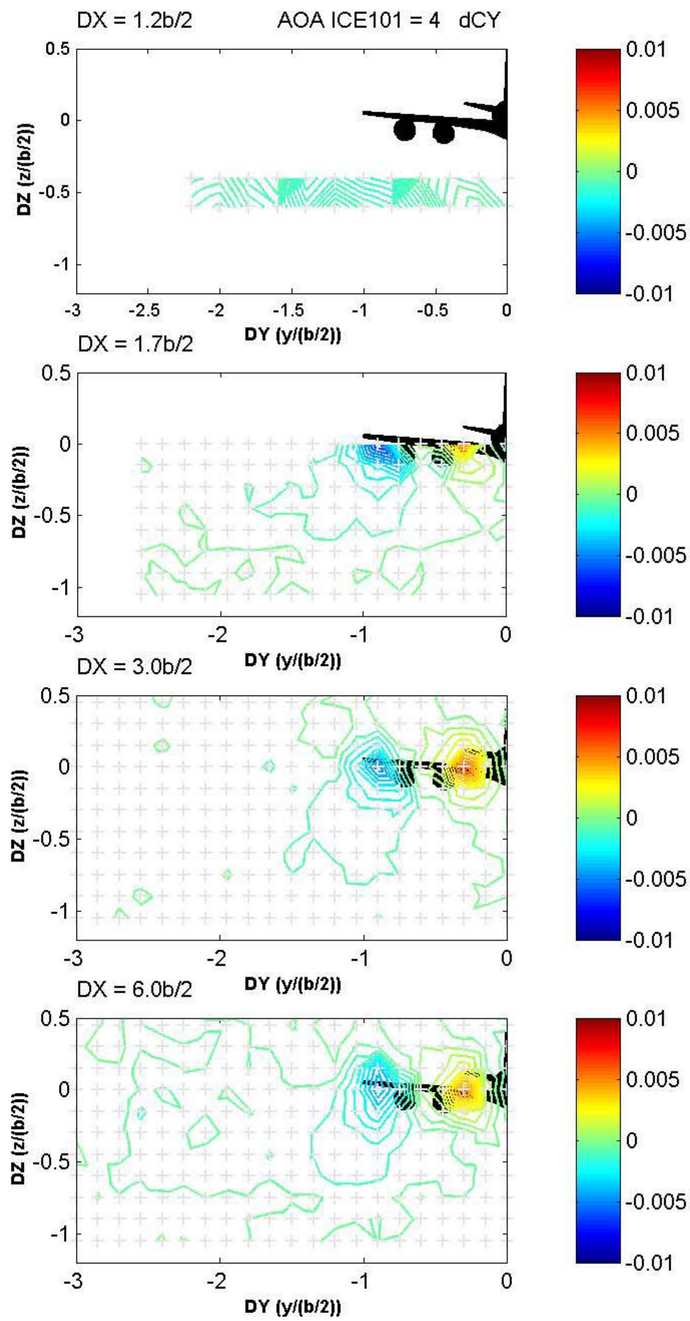


Figure 14. Side force increment produced by KC-135 on ICE 101 at AOA=4°.

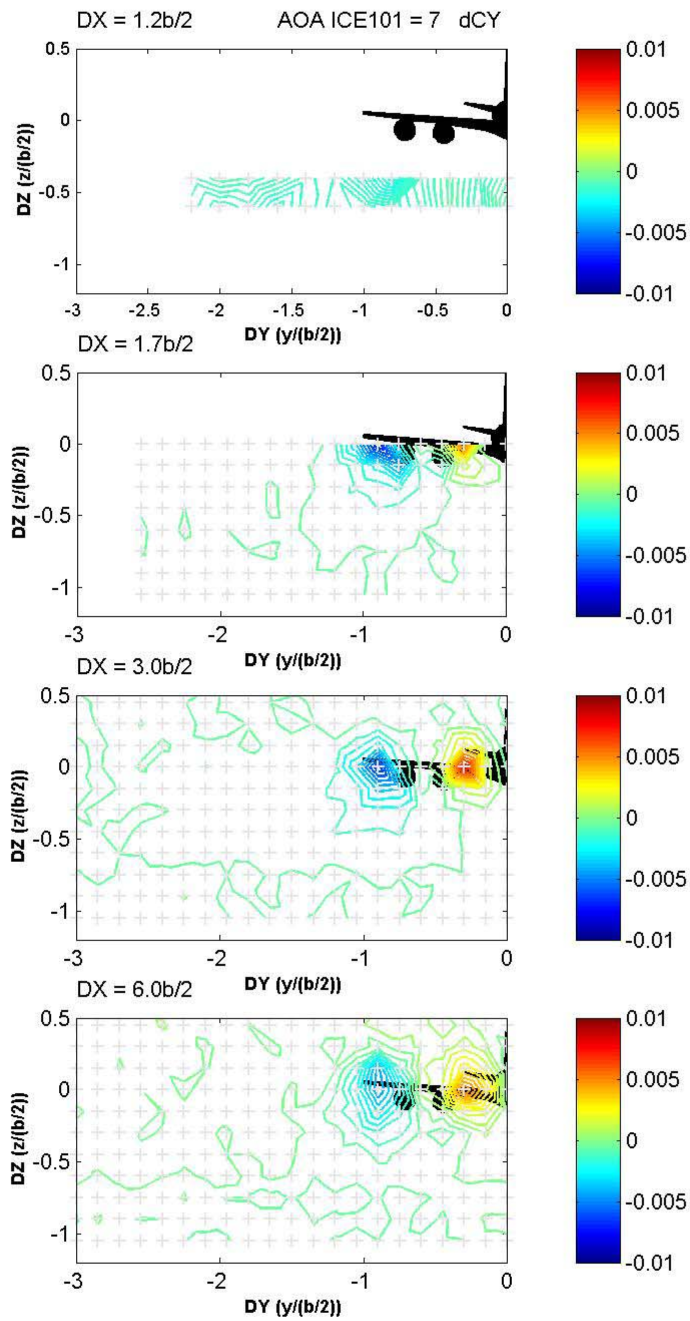


Figure 15. Side force increment produced by KC-135 on ICE 101 at AOA=7°.

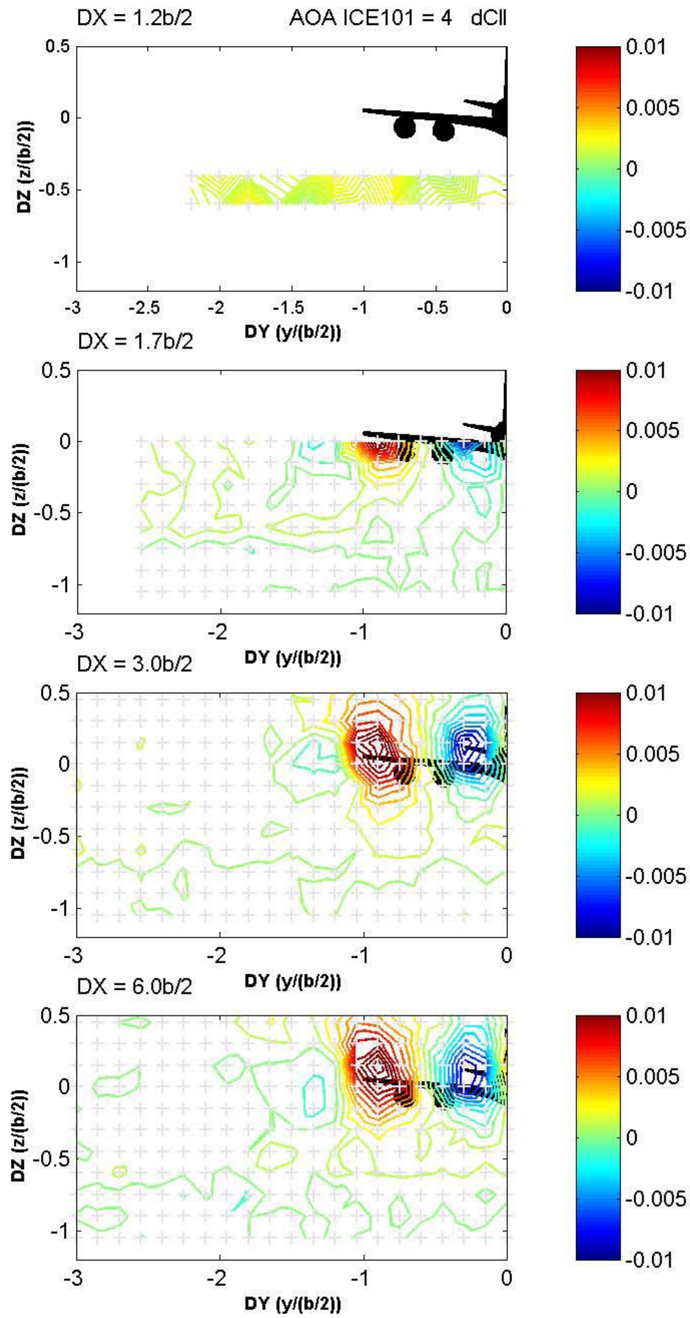


Figure 16. Rolling moment increment produced by KC-135 on ICE 101 at AOA=4°.

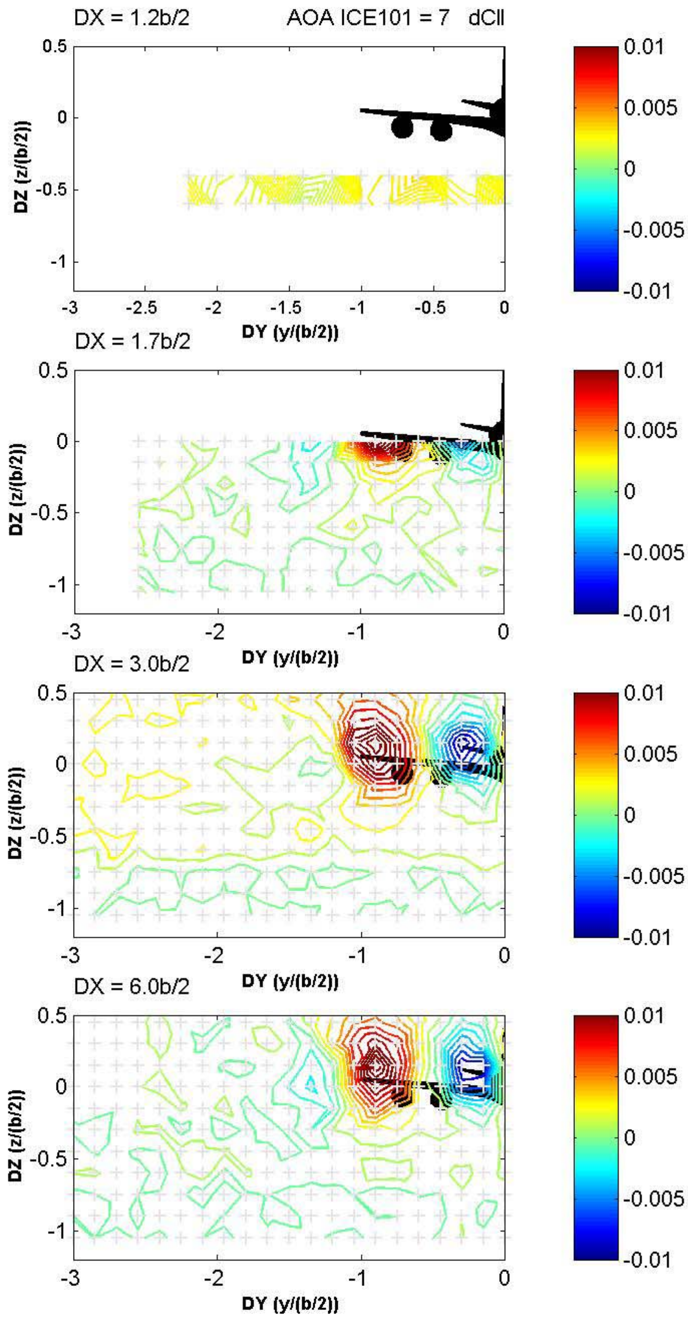


Figure 17. Rolling moment increment produced by KC-135 on ICE 101 at AOA=7°.

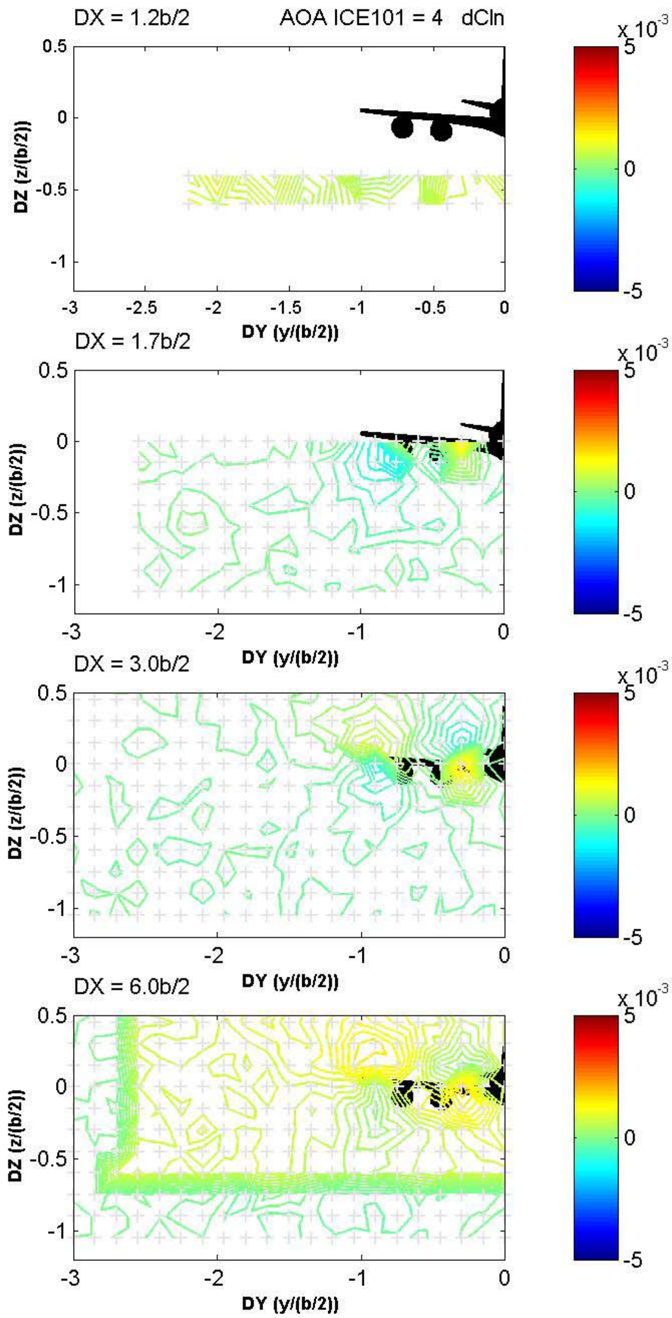


Figure 18. Yawing moment increment produced by KC-135 on ICE 101 at AOA=4°.

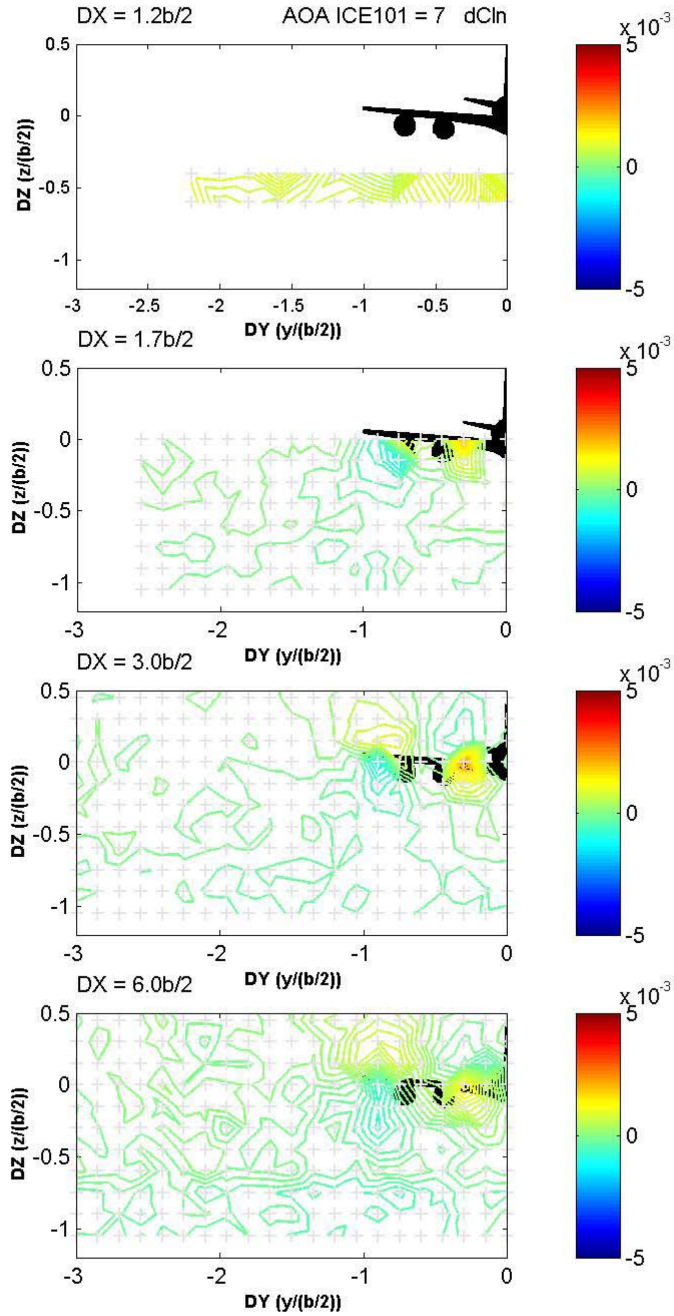


Figure 19. Yawing moment increment produced by KC-135 on ICE 101 at AOA=7°.

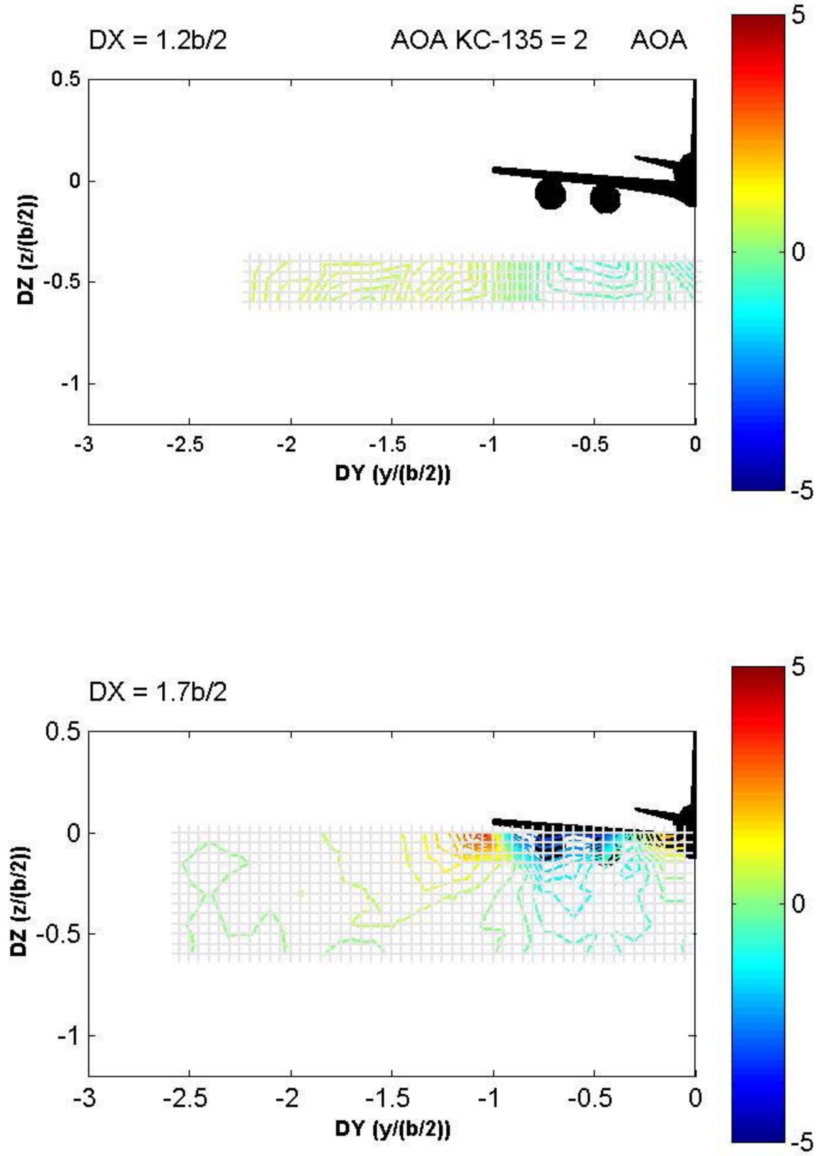
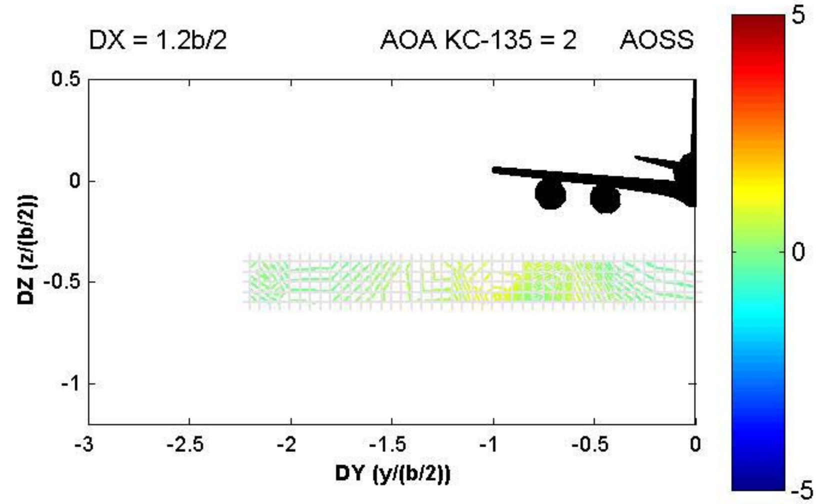


Figure 20. Angle of attack flowfield variations produced by KC-135 at AOA=2°.



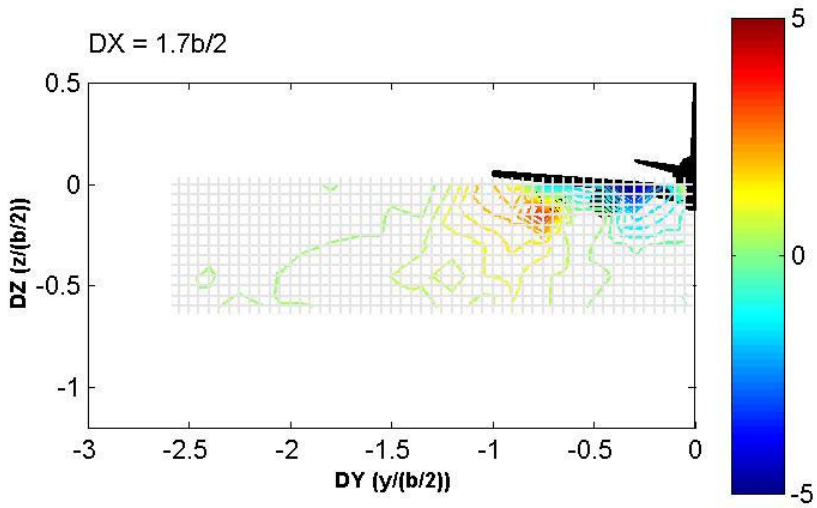


Figure 21. Angle of sideslip flowfield variations produced by KC-135 at AOA=2°.

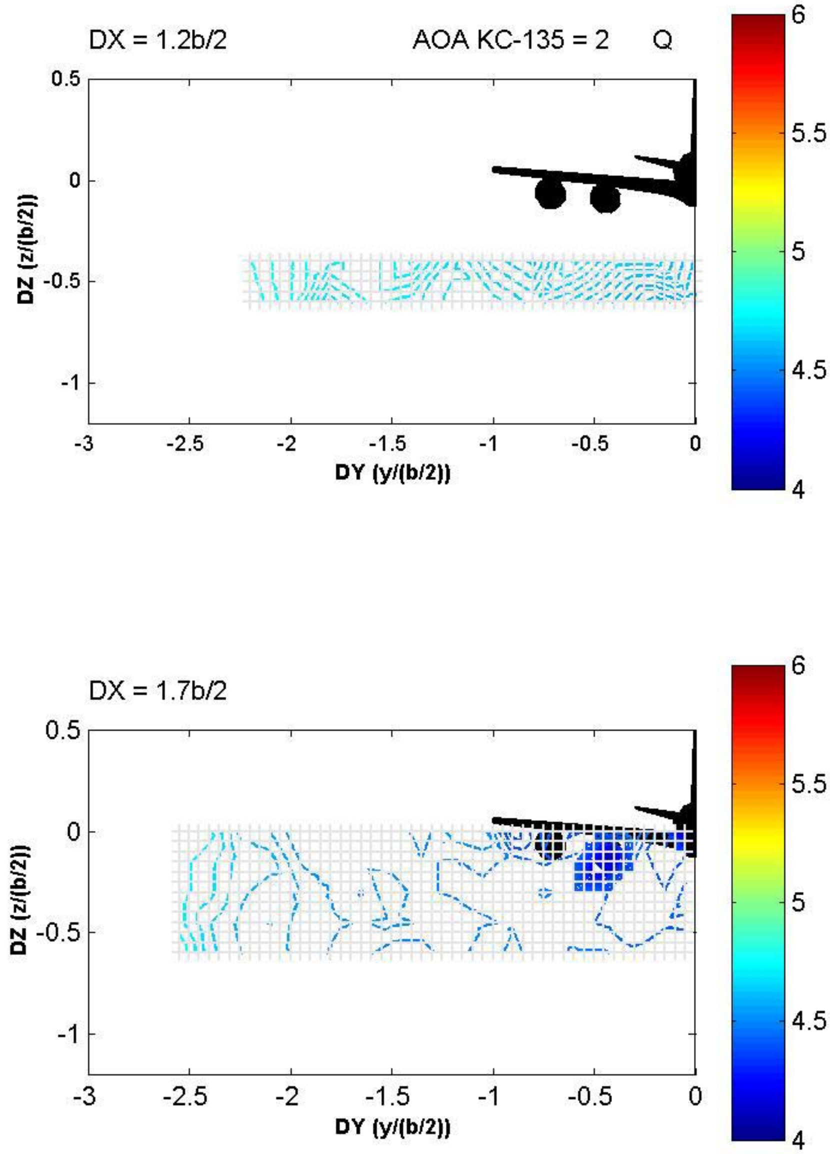


Figure 22. Dynamic pressure flowfield variations produced by KC-135 at AOA=2°.

References

1. Smith, David L., An Efficient Algorithm Using Matrix Methods to Solve Wind-tunnel Force-balance Equations. NASA TN D-6860, August 1972.